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TITLE SOLAR OPACITIES CONSTRAINED BY SOLAR NEUTRINOS AND SOLAR OSCILLATIONS

AUTHOR(S) Arthur N. Cox, T-6

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

SOLAR OPACITIES CONSTRAINED BY SOLAR NEUTRINOS AND SOLAR OSCILLATIONS

Arthur N. Cox
Theoretical Division
Los Alamos National Laboratory

ABSTRACT. This review discusses the current situation for opacities at the solar center, the solar surface, and for the few million kelvin temperatures that occur below the convection zone. The solar center conditions are important because they are crucial for the neutrino production, which continues to be predicted about 4 times that observed. The main extinction effects there are free-free photon absorption in the electric fields of the hydrogen, helium and the CNO atoms, free electron scattering of photons, and the bound-free and bound-bound absorption of photons by iron atoms with two electrons in the 1s bound level. An assumption that the iron is condensed-out below the convection zone, and the opacity in the central regions is thereby reduced, results in about a 25 percent reduction in the central opacity but only a 5 percent reduction at the base of the convection zone. Furthermore, the p-mode solar oscillations are changed with this assumption, and do not fit the observed ones as well as for standard models. A discussion of the large effective opacity reduction by weakly interacting massive particles (WIMPs or Cosmions) also results in poor agreement with observed p-mode oscillation frequencies. The much larger opacities for the solar surface layers from the Los Alamos Astrophysical Opacity Library instead of the widely used Cox and Tabor values show small improvements in oscillation frequency predictions, but the largest effect is in the discussion of p-mode stability. Solar oscillation frequencies can serve as an opacity experiment for the temperatures and densities, respectively, of a few million kelvin and between 0.1 and 10 g/cm^3. Current oscillation frequency calculations indicate that possibly the Opacity Library values need an increase of typically 15 percent just at the bottom of the convection zone at 3×10^6 K. Opacities have uncertainties at the photosphere and deeper than the convection zone ranging from 10 to 25 percent. The equation of state that supplies data for the opacity calculations fortunately has pressure uncertainties of only about 1 percent, but opacity uncertainties will always be much larger. A discussion is given about opacity experiments that the stars provide. Opacities in the envelopes of the Hyades G stars, the Cepheids, δ Scuti variables, and the β Cephei variables indicate that significantly larger opacities, possibly caused by iron lines, seem to be required.

1. INTRODUCTION

The stars have been an important opacity experiment. They have proved that the opacities that we use for calculating photon diffusion in stellar models are correct enough to explain most of the features of stellar evolution. Nevertheless, many details remain to be explained, and the best available laboratory is the Sun. For 30 years precise solar models have been calculated. In the last 20 years these models have mostly been constructed to study how to reduce the emergent neutrino flux to the level observed in the chlorine detector. In the past dozen years renewed interest has arisen because the solar oscillation frequencies have given new data for the internal solar structure. Today the solar structure can produce even more accurate constraints on stellar opacities.

This review discusses several interesting and current topics in solar opacity and structure that impact on the neutrino and oscillation problems. It also briefly touches on related opacity problems for several other classes of stars. For a review of how stellar opacities are calculated readers should consult the first comprehensive exposition by Cox (1965) or the modern update by Huebner (1986). Recent comprehensive tables that are of value in calculating stellar structure have been published by Cox and Tabor (1976). The Los Alamos Astrophysical Opacity Library by Huebner et. al (1977) allows Library users to calculate their own mixtures of hydrogen, helium, and the many other elements. Many tables have been calculated that way and passed around to other stellar astrophysicists all over the world. Hopefully, the Library is easy enough to use accurately, so that these tables are all consistent with each other.

Since the availability of the Library, there have been a few important specialized papers discussing improvements. Magee, Merts, and Huebner (1984) as well as Iglesias, Rogers, and Wilson (1987) have searched for opacity increases for the giant stars. It is hoped that the extensive equation of state (MHD) and opacity investigations by Mihalas, Hummer, Dappen, Seaton, and many others will produce a definitive set of tables for the future.

We discuss in this review the current issues for opacities at the solar center, the solar surface, and in the layers just below the convection zone. We also mention three other experiments that may help constrain opacities. These are the lithium problem of the Hyades G stars, the pulsation periods of the Cepheids and the δ Scuti variables, and the instability of the β Cephei variables.

Many researchers calculating stellar structure use the Los Alamos opacity tables directly using special interpolation procedures. This is what we do also in our pulsation studies at Los Alamos when the part of the star of interest is only the homogeneous composition stellar envelope. However, we have never interpolated between tables. For stellar models in advanced evolution stages, where the composition is changing throughout the model, we use the equation of state and opacity fits of Stellingwerf (1975ab) and Iben (1965 for the EOS and 1975 for the opacities). We find that this is adequate for most all studies, but maybe now solar structure studies have become so sophisticated that we need to interpolate between tables ourselves.

Opacities depend crucially of the details of the equation of state. Thus the Los Alamos equation of state results need to be just as comprehensive as those developed for the MHD equation of state. Not only do we need to know the internal partition function to calculate the degree of ionization of an element to know the mixture pressure and energy, but we also need that same data to enable us to calculate the bound-free and bound-bound photon absorptions that can occur. For many it may be a surprise that our equation of state data are available and agree closely with the MHD results. Just how closely is a topic now receiving interest for both equation of state and opacity studies.

There has been considerable activity lately on the question as to whether stellar opacities need to be increased because many weak lines, especially from iron, have been neglected. This is so even though iron is not a very abundant element in the solar composition. Evidence is growing for selected opacity increases, and in this review we will see that the exact accounting of the iron lines is important for the entire Sun, from the photosphere to the center.

2. THE SOLAR CENTER

Interest in the opacity at the solar center is due mostly to the solar neutrino problem. Two detectable sources, a line at 0.86 Mev and a spectrum extending to 17.98 Mev, respectively, for the ^7Be electron capture and the ^8B radioactive decay, are the main neutrinos that are effectively captured by ^{37}Cl. These fluxes, calculated from a recent solar model constructed by Cox, Guzik, and Kidman (CGK 1989) produce 11 SNU's. This is more than other recent predictions near 8 SNU's, and considerably above the 2 SNU's (Davis, 1986) observed averaged over the last 20 years. Corrections for a known systematic pressure error in the Iben equation of state used for the CGK model reduce the central helium content, the central temperature, and the neutrino output to about the Bahcall and Ulrich (1988) 8 SNU's. But all recent predictions are larger than observations. Can solar opacities be blamed for this persistent prediction of too many neutrinos?

The answer for the last 20 years has been no. The opacity at the center of the Sun is approximately 1/3 free electron scattering, 1/3 free free absorption of photons in the electric field of protons, alpha particles, and CNONe nuclei, and 1/3 due to a bound-free absorption edge and a bound-bound line of highly ionised iron. These absorption effects are simple enough, and the calculation of their attenuation reliable enough, that the opacity at the center of the Sun is probably known to an accuracy of 10 percent. Differences from model to model may be due more to composition changes rather than opacity uncertainties.

Figure 1 shows the monochromatic absorption coefficient versus photon energy at 15×10^6K and a density of 150 g/cm^3, conditions that are close to the solar center as calculated for current standard solar models. These data come from the EXOP opacity program, the immediate forerunner of the MOOP program that calculated the monochromatic absorption and scattering data for the Opacity Library. It has been used for this review because of its convenience in operation and in producing plots. The bound-free photoelectric absorption edge is caused by liberating the 1s electron from the iron atom with 2 1s electrons, 0.6 2s electrons and 1.7 2p electrons. This edge is at the mean position of individual edges for the several ionisation stages present. The line is the sum of the 1s to 2p transitions in the iron ions that are 20, 21, 22, and 23 times ionised. The $1/\nu^3$ variation at photon energies below the absorption edge is the free-free absorption from all the ions in the mixture including those from iron. Above the edge the contribution of the free electron scattering becomes noticeable. The Rosseland mean weighting function peaks at $h\nu/kT = 7.0$, which is just over 9 kev. Significant weight is in the band of 3.5 to 18 kev, so one can roughly confirm that the mean opacity here is 1.18 cm^2/g.

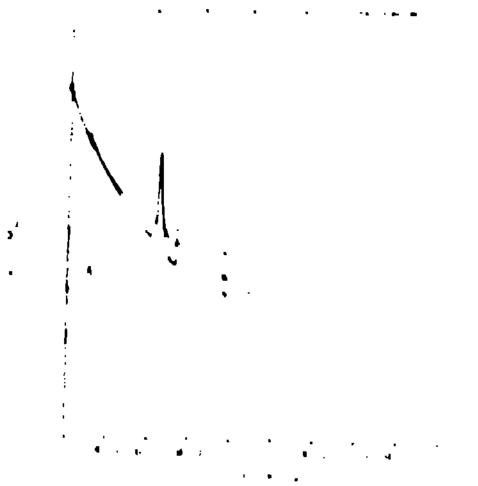
The iron line transition 1s to 3p is not seen because the 3p level is destroyed by the large density of charges surrounding the iron ions. Shielding of the nucleus by the other bound electrons and the continuum depression puts the absorption edge at 7.3 kev instead of at 9.2 kev for the configuration with only one bound electron. The resonant scattering line at 3 kev and weak absorption lines near there are due to the 1s to 2p transitions in argon from ions with 1, 2, and 3 electrons attached.

Figure 2 gives the EXOP monochromatic absorption coefficients for a case at the same temperature and density where the iron is absent. This case has been considered by Dearborn, Marx, and Ruff (1987) as a possible way of reducing the central opacity in solar models, reducing the central temperature, and alleviating the solar neutrino problem. The mean opacity for this case is 0.92 cm^2/g. The iron line and edge are missing, and that results in the 25 percent opacity decrease.

The opacity for the case where all the Z elements are removed from the mixture is 0.80 cm^2/g. The contribution of completely ionised hydrogen and helium in producing free-free absorption and free electron scattering now produces the bulk of the opacity.

At Los Alamos we have been using the solar p-modes as an indicator of the internal solar opacity. That is, in addition to adjusting the mixing length in the standard mixing length convection theory to get the observed solar radius at the current age, and adjusting the original helium content to get the observed luminosity, we also adjust the opacity (at the bottom of the convection zone) to match the observed low degree p-modes. Figure 3 shows the observed minus calculated (O-C) frequencies for l = 1 to 10 in the radial order band where oscillations are observed. The CGK case, with adjusted opacities to be discussed later, match the observations to within about 4 μHz out of the 3000 μHz for these modes. One important point is that opacity tables have not been directly used in the CGK work. Instead, a calibrated Iben (1975) fit is evaluated for the opacities.

The O-C values for the no-iron below the convection zones case are shown in figure 4. While the differences are actually smaller, there is a spread from one l value to the next. This gives a hint that things are worse than for the standard CGK case, but the difference between the two cases is slight.



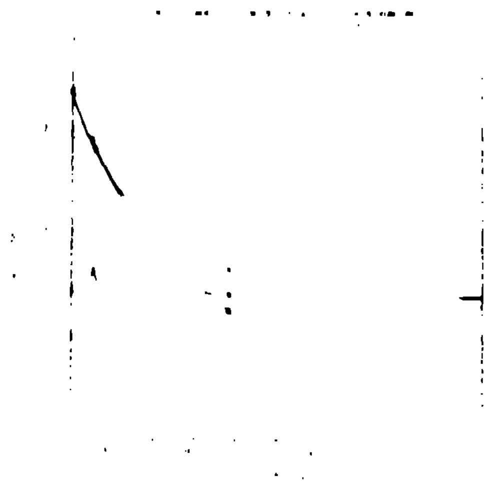
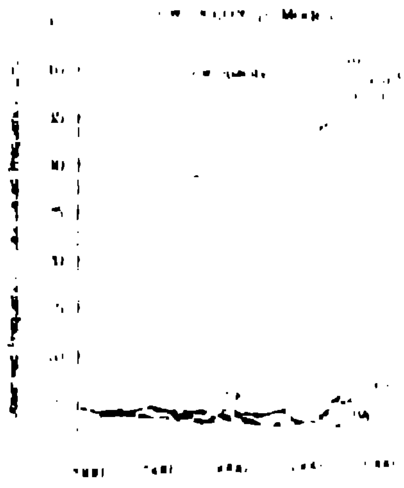


Figure 1. The monochromatic absorption coefficients for a solar mixture for the approximate solar center conditions of 15×10^6 K and 150 g/cm^3. The iron bound-bound and bound-free transitions are seen together with the free-free absorptions from all the ions and the separately shown free electron scattering.

Figure 2. The monochromatic absorption coefficients for a solar mixture without iron for the approximate solar center conditions of 15×10^6 K and 150 g/cm^3. The iron line and bound-free edge are now absent, and the opacity is reduced from 1.18 cm^2/g to 0.92 cm^2/g.



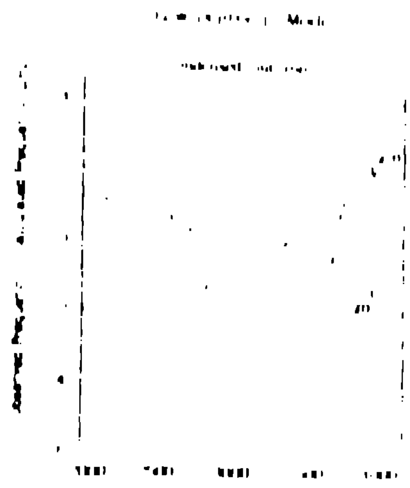


Figure 3. The observed minus the calculated low degree p-mode frequencies for the CGK and the low opacity models discussed in the CGR paper.

Figure 4. The observed minus the calculated low degree p-mode frequencies for the CGR condensed-out iron model.

Figures 5 and 6 show the small difference, which we call $\delta(n)$ for the two models with and without iron. This $\delta(n)$, the difference between the radial and quadrupole mode frequencies, has been discussed by many others (see Cox, Guzik, and Raby, CGR 1989), and it is a sensitive indicator of the central model conditions. Agreement of predictions with the observed frequency differences in the band of radial order 11 to 33, or, where the observations are more accurate, between 20 and 25, indicates that a model represents the actual solar center. We see that both models are in reasonable agreement with observations, with the standard CGK one (normal iron abundance) slightly better.

Collective effects have been frequently discussed as a way of reducing the electron scattering photon attenuation at the solar center. The most recent discussion is by Boercker (1987) who refines the earlier work of Diesendorf and Ninham (1969) and Diesendorf (1970). These latter authors have assumed that the angular dependence of the electron scattering integrated to zero, whereas for the non-vacuum solar conditions it does not. The result is a smaller opacity reduction. The correct reduction is about 25 percent, while the Los Alamos Astrophysical Opacity Library has a reduction at the solar center of about 20 percent, and the scattering in figures 1 and 2 above had no reduction at all. This matter seems to have been settled now, and its uncertainties are small, even though Bahcall and Ulrich (1988) calculate that the correct formulation gives opacities lower than the Opacity Library that is worth about a 9 percent reduction in the emergent calculated neutrino flux.

There is one additional aspect of the collective effects. It seems that only the Los Alamos calculations have included electron degeneracy effects for the Debye radius that enters in the collective effects discussion. The above mentioned 20 percent Los Alamos Astrophysical Opacity Library opacity reduction discussed by Boercker includes this electron degeneracy effect.

Recently there has been this idea that there may be weakly interacting massive particles (WIMPs) that are numerous enough to supply the missing mass of the universe, or at least the missing mass around galaxies including ours. If these particles of about 5 times the proton mass really exist, then the Sun inevitably would collect many of them (one in 10^{11} protons) which would orbit in the inner 10 percent of the mass of the Sun. Even though they have an interaction cross section of only about $10^{-36} cm^2$ with ordinary matter, they are an important source for conduction of energy from the solar center to several times their orbit radius. Stuart Raby has taken the work of others such as Spergel and Press (1985) to give a refined expression for the WIMP or Cosmion opacity. This is:

$$\kappa_{cosmion} = \kappa_0 \left(\frac{T}{T_0}\right)^{3.5} \left(\frac{\rho}{\rho_0}\right)^{-2} exp\left(\frac{r^2}{r_0^2}\right)(r + r_0)/2r.$$

For the total opacity, including the Cosmion effects, the expression

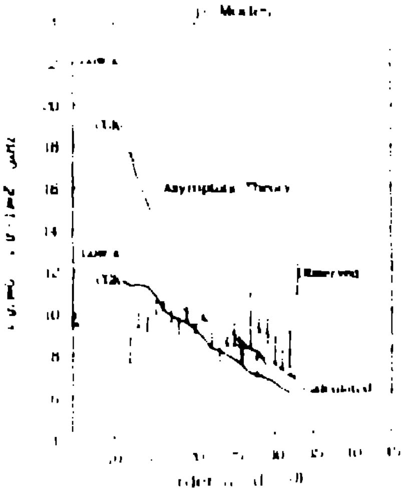
$$1/\kappa_{total} = 1/\kappa_{cosmion} + 1/\kappa_{photon}$$

is used. For the Cosmion opacity the values we have used are $\kappa_0 = 10^{-3}$, $T_0 = 13x10^6$ K, $\rho_0 = 200$ g/cm^3, and $r_0 = 0.0428$ solar radii.

Some workers have simulated the conduction of the Cosmions by considering them as an energy source some distance from the solar center instead of having them merely as another opacity (conduction) contribution. I understand that treating the Cosmion effects by the use of an effective opacity is more appropriate, and it does not lead to any instability problems that a few others (De Luca et al., 1989) have experienced.

With the κ_0 as given, corresponding to the above Cosmion abundance, the neutrino flux produces 2.2 (corrected to 1.5) SNU in the chlorine detector. A second Cosmion case has also been done by CGR (1989) with 9 times fewer Cosmions giving 15.9 times larger opacity, and that neutrino flux gives 4.4 (corrected to 3.5) SNU. This higher neutrino flux is just on the border of being compatible with observations. It is actually lower than the neutrino flux measured in the recent past.

Figure 7 gives again the O-C plot for the same low degree solar p-modes for the two Cosmion models. The opacity adjustment below the convection zone, to be discussed later, is still in the model. That means that this figure can be directly compared to figures 3 and 4 to see the effects of



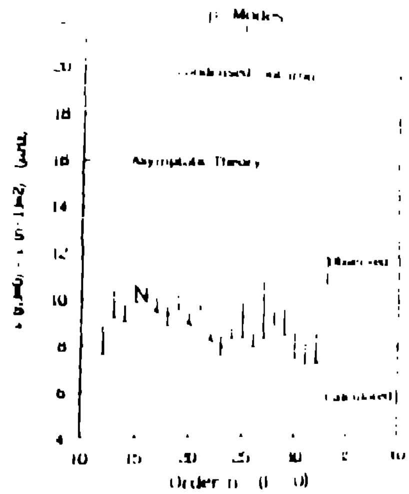
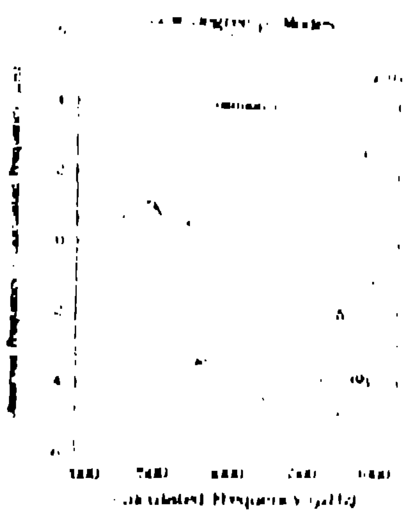


Figure 5. The $\delta(n)$ differences between the radial and quadrupole mode frequencies is plotted versus the radial order for the CGK and the low opacity models. The observations are given with error bars as published by Jimenez et al. (1988). Both the actually calculated eigenvalue frequency differences and the asymptotic theory variations are given.

Figure 6. The $\delta(n)$ differences between the radial and quadrupole mode frequencies is plotted versus the radial order for the condensed-out iron model. The observations are given with error bars as published by Jimenes et al. (1988). Both the actually calculated eigenvalue frequency differences and the asymptotic theory variations are given.



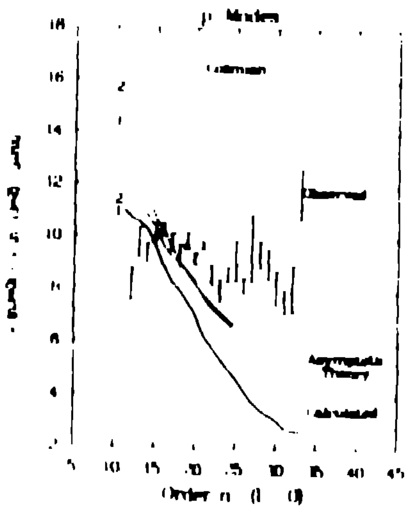


Figure 7. The observed minus the calculated low degree p-mode frequencies for the standard Cosmion model discussed in the CGR paper.

Figure 8. The $\delta(n)$ differences between the radial and quadrupole mode frequencies is plotted versus the radial order for the two Cosmion models. The observations are given with error bars as published by Jimenes et al. (1988). Both the actually calculated eigenvalue frequency differences and the asymptotic theory variations are given.

the Cosmions. The large spread of the differences between observation and prediction indicates that this model is not so good. Figure 8 plots the $\delta(n)$ between the radial and quadrupole modes for this standard Cosmion model and the one where the conduction bv the Cosmions has been reduced by a factor of 15.9. These plots are in an Astrophysical Journal paper by CGR (1989). The reduced Cosmion number model with its marginally acceptable larger neutrino flux still does not fit the observed p-mode frequency differences very well.

In a recent paper by Gilliland and Dappen (1988), it was suggested that WIMPs actually solve the solar neutrino problem. This is because the oscillation $\delta(n)$ values seem to match those observed for models that had considerable number of WIMPs and a suitably low neutrino flux. This result conflicts with the data given here. The explanation probably is that, if the O-C curve is rather positive, as shown in an extreme for our low opacity case in figure 3, then the $\delta(n)$ runs rather high as seen in figure 5. Gilliland and Däppen did not publish their O-C curve, but since they used the Eggleton, Faulkner, and Flannery (1973) equation of state without the coulomb corrections, and they used the old low Cox-Stewart (1970ab) opacities, it is likely that the O-C curve is mostly positive. Then they would have a high $\delta(n)$ curve, which they also did not publish. These authors would need WIMPs to lower the $\delta(n)$, and its mean value they do discuss, by about the amount they have found by using the older equation of state and opacity data.

A final matter concerning the opacity at the solar center is one discussed by Bahcall and Ulrich. During the solar evolution most of the nuclear energy is from the proton-proton reactions, but there is some cycling in the CNO process. This later process converts essentially all the carbon to nitrogen, which is slow to interact in an proton capture reaction. Even some of the oxygen is changed to nitrogen. Bahcall and Ulrich suggest that the opacity at the solar center is increased by 7.6 percent due to this processing. However, my recent detailed studies show that this is an incorrect result. Using a number of calculations, I find that the opacity is increased less than one percent by this composition change.

Table 1 gives some of the comparisons kindly calculated by Joyce Gusik for the Ross-Aller (1976) mixture. This is different from the mixture given by Cox and Tabor 1976) and used for figures 1 and 2. She has used the Opacity Library to show that when all the carbon is assumed to be nitrogen (but the oxygen is unchanged in its abundance), the opacity is increased by less than one percent. The track through the table following the central solar structure is 1.16 kev at a density of 100 and 1.35 kev at a density of 160. Only the Library temperatures have been used to avoid interpolation. Actually the CNO cycling effect gets smaller at higher temperatures and densities, merely reflecting the growing contribution of the free electron scattering. Such an effect would be expected by inspecting figures 1 and 2. All the bound-free edges of the CNO elements are at very low photon energies, and the only relic seen at the kilovolt photon energies and kilovolt temperatures is the free-free photon absorption in the electric fields of the CNO ions.

The extensive work over the last 20 years to reduce the neutrino outout has left us exactly where we were when we started. To solve the solar neutrino problem, I suggest that the neutrinos oscillate between their different types and interact with the electrons in the solar interior as Bethe (1986) and Rosen and Gelb (1986) have suggested. This so-called MSW effect requires neutrinos to have mass and to oscillate between the three different types, but that is not so unreasonable nowadays.

3. THE SOLAR SURFACE

Until the last few years, the opacity for the solar material at and just below the photosphere was obtained from the Cox and Tabor (1976) tables. In late 1979 Norman Magee kindly calculated a special low temperature table for the Ross-Aller (1976) composition using the same improved city program that was used to compile the Los Alamos Astrophysical Opacity Library (Huebner et al.,1977). These opacities included molecules, but they are quite unimportant for solar models. Russell Kidman in 1983 then added Library opacities at the higher temperatures to form the Ross-Aller 1 table that is now widely used by solar modelers. The interesting thing is that even though molecules are included, the main reason for a doubling of the opacity over the Cox-Tabor values is that iron lines are now calculated in much more detail than in the Cox-Tabor tables.

Figure 9 plots the logarithm of the ratio of the opacities from EXOP, as used for the King IVa table, to those from the Ross-Aller 1 table. Both tables have essentially the same composition.

Figure 10 gives the monochromatic absorption coefficients versus photon energy for a temperature of 0.5 electron volt (5800K) and a density of $3x10^{-7}$ g/cm^3. The same plot using the Cox-Tabor data shows only a few scattered lines instead of the forest of iron lines shown in this figure and also actually seen in the solar photosphere spectrum. It is interesting that over ten years ago, Huebner (1978) felt it important to display this very same plot to show the strong influence of the iron lines on the solar photosphere spectrum. Apparently the contour diagram given by Cox (1983) and repeated by Magee, Merts, and Huebner (1984), which shows the effects of lines for astrophysical opacity mixtures, missed a small island with a large opacity increase at a temperature of 0.5 ev. Absorption lines are not important at temperatures lower than 4000K because of the large effects of water vapor molecules, and above 8000K (0.7 ev) hydrogen bound-free absorption becomes dominant.

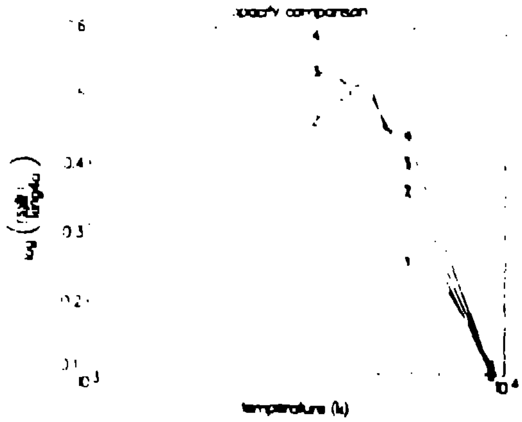
While for solar models we have almost always used the Ross-Aller 1 opacities by calibrating the Stellingwerf (1975ab) fit, others have used the Cox-Tabor opacity tables. Thus we do not directly know the relative effects of these two opacity tables on p-mode frequencies. According to Christensen-Dalsgaard, however, p-mode frequencies fit somewhat better when the newer Ross-Aller 1 opacities are used in the solar model.

I have considered the relative nonadiabatic effects of the King IVa (Cox-Tabor using EXOP) and the Ross-Aller 1 tables for the p_9, l=60 mode observed at 3036 μHz. Figure 11 shows the work to drive pulsations per pulsation cycle versus zone number for the King IVa table in the model and in the oscillation eigensolution. These opacities were used (through the Stellingwerf fit) for the Kidman and Cox (1984) study of nonadiabatic effects on p-modes. The peak driving is at about 9000K. The mode decays approximately as inferred from the observed p-mode line widths in the spectrum. This can be seen from the figure because the integral over the driving (plotted per zone to make the integral easier to see) is slightly negative.

When the Ross-Aller 1 opacities are approximated by actually tripling the Stellingwerf opacity fit values, the pulsation driving is given by figure 12. Driving is now at a higher mass level where the temperature is again about 9000K, because the temperature gradient from the photosphere is steeper. In this case, however, the driving overwhelms the damping, and the mode is pulsationally unstable. Thus the overstability of the solar p-modes depends sensitively on the opacity and monochromatic absorption coefficients.

But care must be taken. Radiation transport effects are not included in these calculations either for the model structure or for the oscillation eigensolutions. Also convection luminosity, which carries perhaps 99 % of the emergent luminosity at the mass level where the p-modes are driven, is treated in our calculations as completely frozen-in. Therefore, a definitive statement about the pulsation driving is not possible. It seems that modern nonadiabatic calculations, for example the radiation transport work by Christensen-Dalsgaard and Frandsen (1983) or the radiation transport and convection studies by Balmford and Gough (1988), need to include the latest Ross-Aller 1 opacities in any case.

Modelers of stellar structure have needed complete opacity tables for many mixtures, but at the moment there are really only two modern ones. The Opacity Library allows opacity calculations only down to 11,600K temperature, because molecular contributions to the absorption become important at temperatures like 6000K. Mixtures named Ross-Aller 1 and Grossman 1 have been used to produce tables down to 2500K. This lack of tables is now being rectified by Weiss at Illinois and Munich who soon will have 20 additional tables, some with significantly different hydrogen and helium contents.



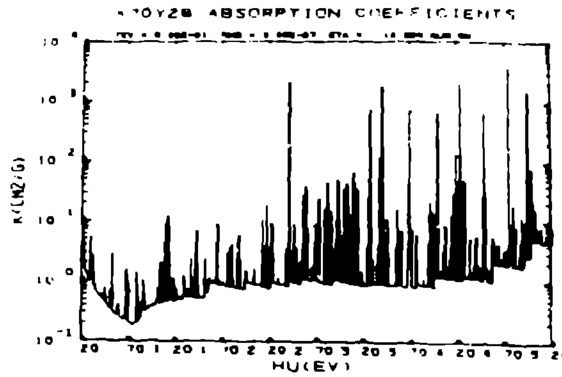
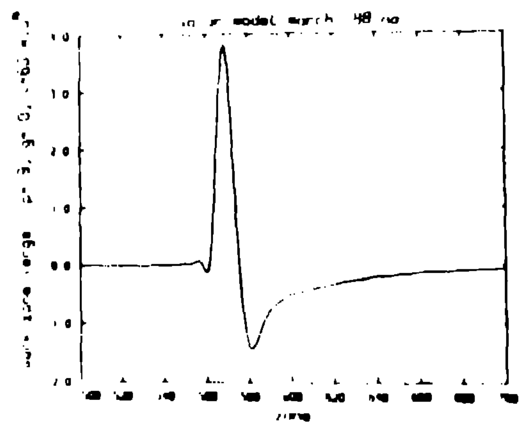


Figure 9. The logarithm of the ratio of the Ross-Aller 1 table opacities to the King IVa table opacities is plotted versus temperature for densities 3x10^{-8}, 1x10^{-7}, 3x10^{-7}, and 1x10^{-6} g/cm^3. At the solar photosphere, the new Opacity Library opacities are twice that from the Cox and Tabor tables.

Figure 10. The monochromatic absorption coefficients for a solar mixture for the approximate solar photosphere conditions of 5800K and 3x10^{-7} g/cm^3. On top of the dominant negative hydrogen ion absorption one can see the myriad of iron lines coming from transitions from the M shell to higher levels.



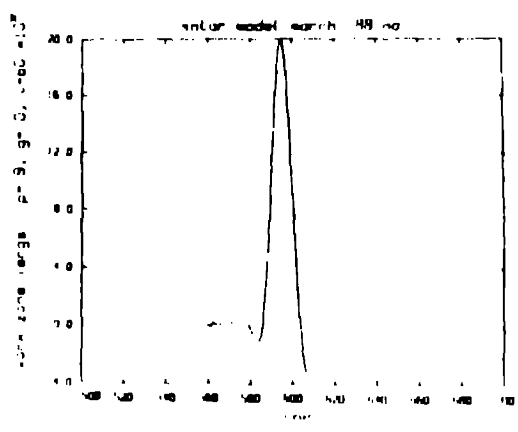


Figure 11. The work per cycle to drive oscillations is plotted versus zone number for the outer 700 zones of the 1700 mass zone CGK model using the Cox and Tabor King IVa opacity table. The peak driving at 9000K is not large enough to destabilize the mode, and this p_0 mode with l=60 decays roughly as actually observed.

Figure 12. The work per cycle to drive oscillations is plotted versus zone number for the outer 700 zones of the 1700 mass zone CGK model using the Opacity Library Ross-Aller 1 opacity table to calibrate the Stellingwerf fit. The peak driving at 9000K is large enough to destabilize the mode, and this p_0 mode with l=60 is predicted to be pulsationally unstable. Other stabilizing effects such as the radiation transport influence on both the photospheric structure and the global oscillations are apparently more dominant.

4. BELOW THE SOLAR CONVECTION ZONE

We have found that the solar p-modes are very sensitive to the opacity just below the convection zone. This sensitivity have been suggested by Christensen-Dalsgaard et al. (1985) and more recently by Korzennik and Ulrich (1989). CGK (1989) adjusted the opacity upward by 15 to 20 percent in the 2 to 7 million kelvin region to get almost perfect agreement with all the low degree p-modes. Recent work by Christensen-Dalsgaard, Lebreton, and Dappen (private communication) has shown that good agreement with the observed p-modes can be found without adjusting the opacity from the Los Alamos Astrophysical Opacity Library at all. Thus only a small or even zero opacity adjustment may eventually be agreed upon.

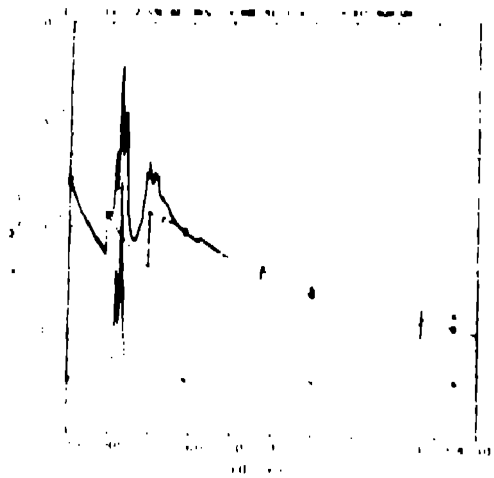
Figure 13 shows the monochromatic absorption coefficients versus photon energy for a temperature of 3×10^6K and a density of 0.4 cm^2/g, calculated by the EXOP opacity program. These conditions for the Cox-Tabor composition obtain just below the solar convection zone. The strong bound-free edge at 0.76 kev photon energy is from oxygen with 0.3 electron in the 1s level. The other strong bound-free edge is from neon at 1.18 kev with 0.9 electron in its K shell. The only other significant K edge is at 3.86 kev from argon with both of its 1s electrons attached, but the K edges of magnesium, aluminum, and silicon can just barely be seen. The carbon K edge is off scale to the left, and the iron K edge is of scale to the right. The edges at 1.4 kev are the L edges of iron with 4.7 electrons in the 2s and 2p levels.

What can cause the opacity uncertainty at these solar conditions? It does not seem that the CNONe ion hydrogen-like bound-free absorptions can be in error very much. Or can the small free-free absorption be uncertain? The electron scattering, with the iron resonance lines near 0.9 kev is small compared to other processes. It very well could be that the absorption lines that are all from transitions with the lower level being 2s or 2p in 15, 16, 17, 18, and 19 times ionized iron are much more numerous than we have indicated. The transitions to level 3s, 3p, and 3d are near 0.9 kev, while the 2 to 4 and 2 to 5 transitions are range from 1.0 to 1.4 kev, just up to the L edges. Note that the level 6 in iron is destroyed by the continuum depression from neighboring charged particles. There is also the possibility that with almost 0.7 electron in the 3 shell levels that there can be some 3 to 3 iron line transitions, which we are not considering. It is not at all unreasonable that the opacity might need to be increased 20 percent for this temperature and density. I predict that the missing opacity is due to the iron lines that are only partially displayed in figure 13.

We have calibrated the Iben (1975) opacity fit to calculate our solar models and to solve for our oscillation eigensolutions. For this case, we have found that a factor of 1.3 on a term called A_s and a factor of 2.0 on the term κ_e correct the Iben fit opacities to the Opacity Library values and then increase them by 15 to 20 percent in the temperature range of 2 to 7 million kelvin. Figure 14 shows the logarithm of the Ross-Aller 1 opacity to the Iben fit opacity ratio versus temperature for the three densities available in the Ross-Aller 1 table. The original Iben fit is 20 to 40 percent too low in the bottom layers of the convection zone and deeper to a temperature of 1.0×10^7K. Figure 15 gives the fit calibrated as stated above relative to the Ross-Aller 1 table. Now the calibration factors make the opacity larger by 20 percent at 3×10^6K and less than 10 percent at 1.0×10^7K.

Figure 3 shows the O-C plot for the two Iben fit cases discussed above. The original Iben fit gives very low opacities in the region below the convection zone, and the fit to the low degree p-mode frequencies is very poor. The dramatic improvement, providing that the equation of state is otherwise accurate, can be used to verify the accuracy of the solar opacities.

The $\delta(n)$ that corresponds to the low opacity case of figure 3 is given in figure 5. The larger figure 3 O-C values give larger $\delta(n)$ values. The sensitivity to the opacity decreases above $l=10$, because the higher degree modes have turning points nearer to the convection zone bottom or even in it. Then the amplitude in the deeper evanescent regions is not large enough to affect significantly the oscillation periods.



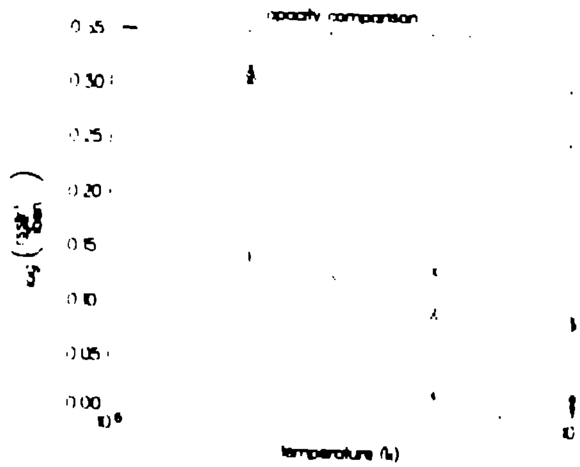


Figure 13. The monochromatic absorption coefficients for a solar mixture for the approximate solar conditions below the convection zone of 3×10^6K and 0.4 g/cm^3. Absorption K edges of oxygen, neon, magnesium, aluminum, silicon, and argon can be seen. Also at 1.4 kilovolt photon energy weak closely spaced L edges of iron are visible.

Figure 14. The logarithm of the ratio of the Ross-Aller 1 table opacities to the Iben fit procedure opacities is plotted versus temperature for densities 1×10^{-1}, 1×10^{0}, and 1×10^{1} g/cm^3. At these conditions, the new Opacity Library opacities are considerably larger than those from the Iben fit originally calibrated to the Cox-Stewart opacities.

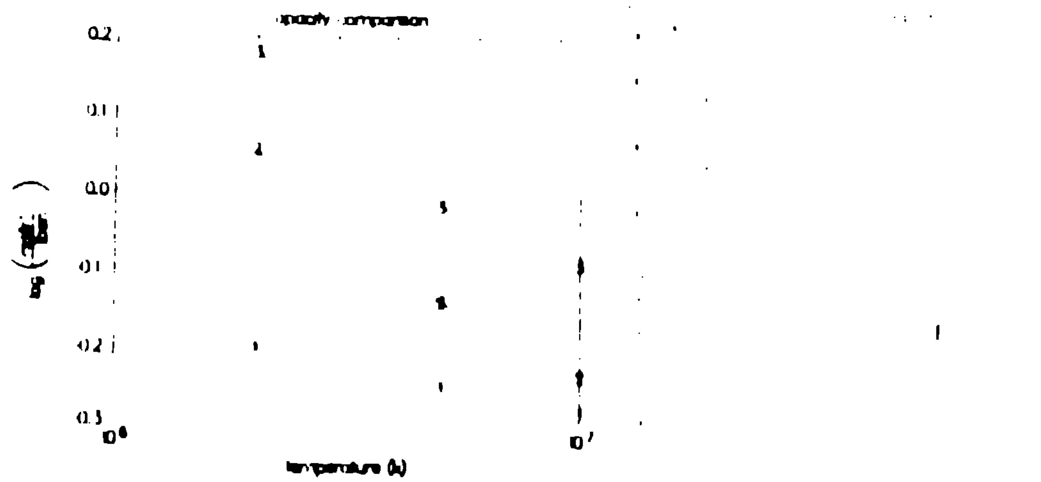


Figure 15. The logarithm of the ratio of the Ross-Aller 1 table opacities to the modified Iben fit procedure opacities is plotted versus temperature for densities 1×10^{-1}, 1×10^{0}, and 1×10^{1} g/cm^3. At these conditions, the modified Iben fit gives opacities 15 to 20 percent larger than the Library, and these opacities give a model that has oscillation frequencies very close to those observed.

Figure 16. The work per cycle to drive oscillations is plotted versus zone number for the 400 zones of a typical β Cephei model using the opacities suggested by the Rossnyai paper. The peak driving at 170,000K in zone 270 is large enough to destabilize this low order $l = 2$ mode. The sharp dip at 800,000K is due to the return to the normal Iben fit procedure for the opacities.

5. OPACITY EXPERIMENTS

For a long time I have been interested to see what the stars can tell about the opacity of their material. We have seen that the Sun can give information about opacities from its central regions, its surface structure, and its structure at and below the convection zone. At the center, we conclude that opacities are reasonably accurate, because we can accurately predict the actual observed low degree p-modes. If ever the g-mode periods of Hill and his colleagues can be confirmed, there will be an even stronger verification of the solar center opacities. These published g-mode periods are very near that expected for the standard solar model without any internal mixing during its life. It does seem that conduction by Cosmions is not supported by current g-mode period observations.

Solar surface opacities are not strongly constrained by either p-mode periods or by their stability.

In the region below the convection zone, we have a rather interesting opacity experiment. CGK have suggested a needed increase, but Christensen-Dalsgaard and collaborators find that an increase is not so necessary. The issue of the importance of iron lines, seen at the convection zone bottom, arises again in the context of the G stars in the Hyades cluster and for classical variable stars.

There is a problem with the predictions for the lithium abundance in the Hyades cluster G stars. Stringfellow, Swenson, and Faulkner (1987) have brought attention to this problem that may be important for stellar opacities. It appears that the convection zone depth in current stellar models needs to be increased rather like that to predict correctly the solar p-mode frequencies and even the solar lithium depletion. A modest opacity increase would very much help this discrepancy with observations that show lithium depletion (presumably by nuclear processing) occurs for hotter G type stars than the experts predict with classical opacity values. Can the iron lines increase the opacity and solve this problem?

Andreasen and Petersen(1988) and Andreasen (1988) have pointed out that a large opacity increase suggested by Simon (1982) to solve a period ratio problem for the classical double-mode Cepheids can also help with period predictions in δ Scuti and RR Lyrae variables. This opacity increase has been discussed by Magee, Merts and Huebner (1984), and such a large increase over such a large temperature range was not found likely. Iglesias, Rogers, and Wilson (1987) however, have found that the forest of iron lines can increase the opacity by modest amounts at 20 ev (230,000K) temperature. Their latest unpublished results cite a factor of 2.2 opacity increase at a density of $10^{-5}\ g\ cm^{3}$, but that temperature-density pair is found only in the yellow giant stars.

More recently Rozsnyai (1989) has proposed even more iron lines, and he finds very large opacity increases. A factor of 3 over that from the Simon model seems to exist at about 250,000K. This opacity increase starts at 150,000K and persists out to 800,000K. Maybe Rozsnyai has found the missing ingredient for Cepheid, δ Scuti, and RR Lyrae star models.

For years, there has been the problem of how the β Cephei variables pulsate. Investigations of many possible mechanisms has always shown, with careful study, that they cannot make these stars unstable, at least in the linear nonadiabatic theory. I now think that increased opacities may give a larger opacity derivative with respect to temperature and be the cause of B star pulsations!

I have increased B star opacities just as Rozsnyai has suggested. At 150,000K the opacities are those from the Opacity Library times a factor that linearly increases to three at a temperature of 170,000K. Then the opacities remain at three times the Library values up to 200,000K. A slow decrease is then followed out to a unity factor again at 800,000K. This profile matches reasonably well the results of both Rozsnyai and of Iglesias, Rogers, and Wilson, but it is at odds with the Los Alamos result of Magee, Merts, and Huebner (1984).

Let me recall an experiment that I did 25 years ago. In a mixture suggested by Aller (1961), I tripled the widths of all the lines in the opacity calculation. Changes of the order of only 30 percent were found, and iron was not an important component of the solar opacity. Nowadays the iron abundance is ten times larger in the solar mixture, and an opacity increase by tripling the line widths is much larger. The Rossnyai increase is not unreasonable.

Figure 16 shows the work plot for a 400 zone model of a typical β Cephei variable at 12 M. With the rapid opacity increase with temperature, caused by the assumed sudden onset of the myriad of iron lines, the normal κ effect produces adequate driving in the pulsation driving region of 150,000K to 300,000K. Can these opacities be correct? It seems that the stars tell us so.

Not every B star is a β Cephei variable, even when they evolve into the strip defined by the many variables known. This fact is clearly seen in some galactic clusters where relative luminosities are not an unknown factor. I suggest that the overstability is indeed a function of the iron abundance. With a normal solar iron abundance, there may not be enough driving, but if there is only a slight iron enhancement (but not due to gravitational settling or radiation levitation that we calculate to be a small effect, however), then the iron lines can have an significant effect on the stellar opacity and stellar stability.

6. REFERENCES

Aller, L. H. 1961. *The Abundance of the Elements*, (New York: Interscience Publishers).

Andreasen, G. K., 1988. Stellar consequences of enhanced metal opacity. I. An attractive solution of the Cepheid period ratio discrepancies. *Astron. Astrophys.*, **201**, 72.

Andreasen, G. K. and Petersen, J. O. 1988. Double mode pulsating stars and opacity changes. *Astron. Astrophys.*, **192**, L4.

Bahcall, J. N. and Ulrich, R. K. 1988. Solar models, neutrino experiments, and helioseismology. *Rev. Mod. Phys.*, **60**, 297.

Balmford, N. J. and Gough, D. O. 1988. Radiative and convective influences on stellar pulsational stability. *Seismology of the Sun and Sun-Like Stars*, ESA SP 286, ed. E. J. Rolfe, p. 47.

Bethe, H. A. 1986. Possible explanation of the solar neutrino puzzle. *Phys. Rev. Lett.*, **56**, 1305.

Boercker, D. B. 1987. Collective effects on Thomson Scattering in the solar interior. *Ap. J. Lett.*, **316**, L95.

Christensen-Dalsgaard, J., Duvall, T. L., Gough, D. O., Harvey, J. W., and Rhodes, E. J. 1985. Speed of sound in the solar interior. *Nature*, **315**, 378.

Christensen-Dalsgaard, J. and Frandsen, S. 1983. Radiative transfer and solar oscillations. *Solar Physics*, **82**, 165.

Cox, A. N. 1965. Stellar absorption coefficients and opacities. *Stars and Stellar Systems*, **8**, eds. L. H. Aller and D. B. McLaughlin (Chicago: University of Chicago Press) p. 195.

Cox, A. N. 1983. Stability problems with an application to early type stars. presented at Swiss Society of Astrophysics and Astronomy, Saas Fee, Switzerland, 1983, Mar 21-26.

Cox, A. N., Guzik, J. A. and Kidman, R. B. 1989. Oscillations of solar models with internal element diffusion. *Ap. J.*, **342**, 1187.

Cox, A. N., Guzik, J. A., and Raby, S. 1989. Oscillations of condensed-out iron and common solar models. *Ap. J.*, submitted.

Cox, A. N. and Stewart, J. N. 1970a. Rosseland opacity tables for population I compositions. *Ap. J. Suppl.*, **19**, 243.

Cox, A. N. and Stewart, J. N. 1970b. Rosseland opacity tables for population II compositions. *Ap. J. Suppl.*, **19**, 261.

Cox, A. N. and Tabor, J. E. 1976. Rosseland opacity tables for 40 stellar mixtures. *Ap. J. Suppl.*, **31**, 271.

Davis, R. 1986. *Report to the Seventh Workshop on Grand Unification*, (ICOBAN '86, Toyama, Japan), p. 237.

Dearborn, D. S. P., Marx, G., and Ruff, I. 1987. A classical solution for the solar neutrino puzzle. *Prog. Theo. Phys.*, **77**, 12.

DeLuca, E. E., Griest, K., Rosner, R., and Wang, J. 1989. On the effects of cosmions upon the structure and evolution of very low mass stars. *Ap. J. Lett.*, submitted.

Diesendorf, M. O. 1970. Electron correlations and solar neutrino counts. *Nature*, **227**, 266.

Diesendorf, M. O. and Ninham 1969. The effect of quantum correlations on electron-scattering opacities. *Ap. J.*, **156**, 1069.

Eggleton, P. P., Faulkner, J. and Flannery, B. P. 1973. An approximate equation of state for stellar material. *Astron. Astrophys.*, **23**, 325.

Gilliland, R. L. and Däppen, W. 1988. Oscillations in solar models with weakly interacting massive particles. Ap. J., **324**, 1153.

Huebner, W. F. 1978. *Proc. Informal Conf. on Status and Future of Solar Neutrino Research*, BNL Rept. 50879, ed. G. Friedlander vol 1, p. 107.

Huebner, W. F. 1986. Atomic and radiative processes in the solar interior. Physics of the Sun, (Dordrecht: D. Reidel Publishing Company), **1**, p. 33.

Huebner, W. F., Merts, A. L., Magee, N. H., and Argo, M. F. 1977. Astrophysical Opacity Library, Los Alamos Scientific Laboratory Report, LA-6760-M.

Iben, I. 1965. Stellar evolution I. The approach to the main sequence. *Ap. J.*, **141**, 993.

Iben, I. 1975. Thermal pulses, p-capture, α-capture s-process nucleosynthesis; and convective mixing in a star of intermediate mass. *Ap. J.*, **196**, 546.

Iglesias, C. A., Rogers, F. J., and Wilson, B. G. 1987. Reexamination of the metal contribution to astrophysical opacity. *Ap. J. Lett.*, **322**, L45.

Jiménez, A., Pallé, P. L., Perez, J. C., Régulo, C., Roca Cortés, T., Isaak, G. R., McLeod, C. P., and van der Raay, B. B. 1988. The solar oscillations spectrum and the solar cycle. *Advances in Helio- and Asteroseismology*, IAU Colloquium 123, eds. J. Christensen-Dalsgaard and S. Frandsen, p. 208.

Kidman, R. B. and Cox, A. N. 1984. The stability of the low degree five minute solar oscillations. in *Solar Seismology from Space*, eds. R. K. Ulrich, J. Harvey, E. J. Rhodes, and J. Toomre, (NASA Pub 8484), p. 335.

Korzennik, S. G. and Ulrich, R. K. 1989. Seismic analysis of the solar interior I. Can opacity changes improve the theoretical frequencies? *Ap. J.*, **339**, 1144.

Magee, N. H., Merts, A. L., and Huebner, W. F., 1984. Is the metal contribution to the astrophysical opacity incorrect? *Ap. J.*, **283**, 264.

Rosen, S. P. and Gelb, J. M. 1986. Mikheyev-Smirnov-Wolfenstein enhancement of oscillations as a possible solution to the solar neutrino problem. *Phys. Rev.*, **D34**, 969.

Ross, J. E. and Aller, L. H. 1976. The chemical composition of the sun. *Science*, **191**, 1223.

Rozsnyai, B. F. 1989. Bracketing the astrophysical opacities for the King IVa mixture. *Ap. J.*, **341**, 414.

Simon, N. R. 1982. A plea for reexamining heavy element opacities in stars. *Ap. J. Lett.*, **260**, L87.

Spergel, D. N. and Press, W. H. 1985. Effect of hypothetical, weakly interacting, massive particles on energy transport in the solar interior. *Ap. J.*, **294**, 663.

Stellingwerf, R. F. 1975a. Modal stability of RR Lyrae stars. *Ap. J.*, **195**, 441.

Stellingwerf, R. F. 1975b. Nonlinear effects in double-mode Cepheids. *Ap. J.*, **199**, 705.

Stringfellow, G. S., Swenson, F. J., and Faulkner, J. 1987. Is there a classical Hyades lithium problem? *BAAS*, **19**, 1020.

Table 1. Central Solar Opacities (cm^2/g), Ross-Aller Mixture

Density(g/cm^3)	1.00 kev Normal	1.00 kev No C	1.25 kev Normal	1.25 kev No C	1.50 kev Normal	1.50 kev No C
100	1.849	1.869	1.178	1.186	0.862	0.866
120	2.022	2.047	1.269	1.279	0.915	0.919
150	2.264	2.294	1.395	1.407	0.986	0.990
160	2.326	2.356	1.435	1.447	1.008	1.012